Reduced Turbine Emissions Using Hydrogen-Enriched Fuels

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Objectives

- Quantify effect of hydrogen addition on gas turbine combustion and emissions.
- Establish a scientific and technological database for lean combustion of hydrogen-enriched fuels in gas turbines.
- Establish numerical simulation capabilities that will facilitate design optimization of hydrogen and hydrogen-enriched lean gas turbine combustors.
- Develop criteria for use of hydrogen addition as a control knob to eliminate instabilities related to varying product gas composition.

Technical Barriers

- The addition of hydrogen to hydrocarbon fuels affects flame stability, combustor acoustics, pollutant emissions and combustor efficiency. Few of these issues are clearly understood.
- Designing a system that can operate over a wide range of fuels while controlling emissions is a challenging task.

Approach

- Design and fabricate a lean premixed swirl burner that simulates the basic features of gas turbine combustors.
- Apply advanced experimental diagnostics to understand fluid dynamics, combustion chemistry, and pollutant formation.
- Develop a computational model for combustor performance in parallel with the experimental program based on next generation Large Eddy Simulation (LES) technique. Use experimental database for model validation.
- Identify problem areas in practical gas turbine combustors where hydrogen enrichment of hydrocarbon fuels could be beneficial.

Accomplishments

- Characterized operation of lean premixed swirl burner over a range of conditions.
- Quantified effect of H_2 addition on lean flame stability and characterized flame structure. Selected target flame conditions for detailed experimental study and model validation.
- Fabricated atmospheric- and high-pressure versions of a lean premixed swirl burner in collaboration with National Energy Technology Laboratory (NETL).
- Selected General Electric Aircraft Engines (GEAE) swirlcup injector to evaluate the advantages of H_2-addition in a production fuel injector. Completed hardware for installation of swirlcup injector in test stand.

- Formed new collaboration with Pratt and Whitney to evaluate a production fuel injector for use with H_2-blended fuels.
- Continued international effort through International Energy Agency (IEA) to address H_2-enriched hydrocarbon fuels for low emission, high efficiency gas turbine combustion. Defined program elements and identified modeling and experimental task areas.

Future Directions

- Complete detailed mapping of velocity field for model validation in the nonreacting swirl burner. Obtain detailed measurements of the velocity, temperature, species concentration fields and exhaust emissions under reacting conditions. Quantify effects of H_2 addition.
- Establish a representation of flow characteristics in the swirl burner using the LES model approach.
- Establish a framework for modeling hydrogen-enriched lean premixed combustion in the presence of acoustically-active flame processes.
- Complete development of test matrix for GEAE swirlcup fuel injector and perform testing. Identify areas where hydrogen enrichment could be beneficial.
- Continue the formation of a broad consortium of industrial partners.
- Continue development of international collaborations through the IEA.

Introduction

The development of advanced combustion capabilities for gaseous hydrogen and hydrogen-blended hydrocarbon fuels in gas turbine applications is an area of much current interest. Driving this interest are several current needs. One need is the cost-effective utilization of alternative fuels with a wide range of heating values. For example, fuels containing significant amounts of hydrogen are often produced as a by-product in coal gasification combined cycle installations. These product gases could provide a significant source of cost-effective fuel for gas turbines. A second need is related to the recognition that ultra-lean premixed combustion is an effective approach to NO_x emission reduction from gas turbine engines. Hydrogen blended with traditional hydrocarbon fuels significantly improves flame stability during lean combustion and allows stable combustion at the low temperatures needed to minimize NO_x production.

A longer-term need is the desire to eliminate unburned hydrocarbon (UHC) and CO_2 emissions. Gas turbines account for 15% of U.S. CO_2 emissions, which is a significant fraction of the total current CO_2 emissions. This number will increase to nearly 30% as natural gas turbines replace older coal-fired steam generation plants. The use of hydrogen-blended hydrocarbon fuels thus provides both a solution to the immediate need for NO_x reduction and also a transition strategy to a carbon-free energy system in the future.

Approach

The addition of hydrogen to hydrocarbon fuels affects both the chemical and physical processes occurring in flames. These changes affect flame stability, combustor acoustics, pollutant emissions and combustor efficiency. Few of these issues are clearly understood. This project will investigate issues surrounding the use of hydrogen and hydrogen-enriched hydrocarbon fuels in gas turbines. Both experimental and modeling approaches are being utilized. The experimental data will be obtained using an array of advanced laser diagnostic techniques that provide information on flame structure, fluid dynamics, combustion gas species concentrations and temperature. These measurements, in addition to providing direct insights into the effects of hydrogen enrichment on combustion and pollutant emissions, will provide the technological database needed for the parallel development of a numerical code, based on the LES technique, to simulate lean premixed combustion of hydrogen and hydrogen-enriched fuels. Close collaborations have been developed with industrial partners to provide a mechanism for the transfer of this technology to practical applications in stationary and aircraft gas turbines. These collaborations will facilitate the identification of problematic areas related to practical gas turbine design and hardware. Areas where hydrogen addition could prove beneficial will be identified, and the potential merits of hydrogen-enriched hydrocarbon fuels will be demonstrated.

Results

The lean premixed swirl burner shown in Figure 1 is representative of land-based industrial applications. This burner will be used to study combustion of hydrogen and hydrogen-blended hydrocarbon fuels. The design emphasizes well-characterized flow and boundary conditions to facilitate the development of a database for LES model validation. Emphasis with regard to LES has been placed on providing support calculations for design purposes and establishing an initial baseline-modeling framework for treatment of hydrogen-enriched, premixed methane flames. The burner design is operationally relevant to industrial devices and is optimally tuned for flow and diagnostic capabilities at the Sandia Combustion Research Facility.

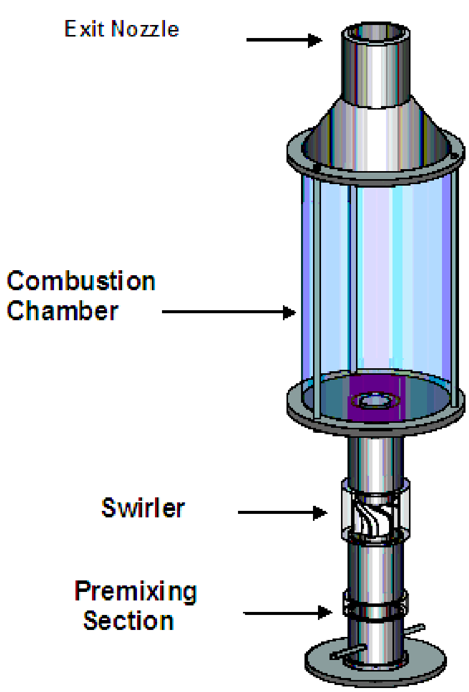

Figure 1. Lean Premixed Swirl Burner Designed to Study Combustion of Hydrogen and Hydrogen-Blended Hydrocarbon Fuels

The stability and burning characteristics of fuel-lean hydrogen/methane/air flames were characterized over a range of operating conditions in the swirl burner. Figure 2 shows the effect of hydrogen addition on flame stability, where the variable n_{H2} is the fraction of hydrogen in the fuel (n_{H2}=0 corresponds to pure methane and n_{H2}=1 is pure hydrogen). The equivalence ratio, f, is a measure of the fuel/air ratio. These measurements were obtained by igniting the flame and then decreasing the fuel/air ratio until the flame completely extinguished, or blew out. The flame typically becomes unstable as the blowout condition is approached. Increasing the hydrogen content from 0% to 20% results in a significant shift in flame blowout conditions to leaner fuel/air ratios. Since operation at leaner fuel/air ratios results in a lower flame temperature and reduced NO_x emissions, hydrogen addition will allow stable operation at the lean conditions needed to limit NO_x emissions.

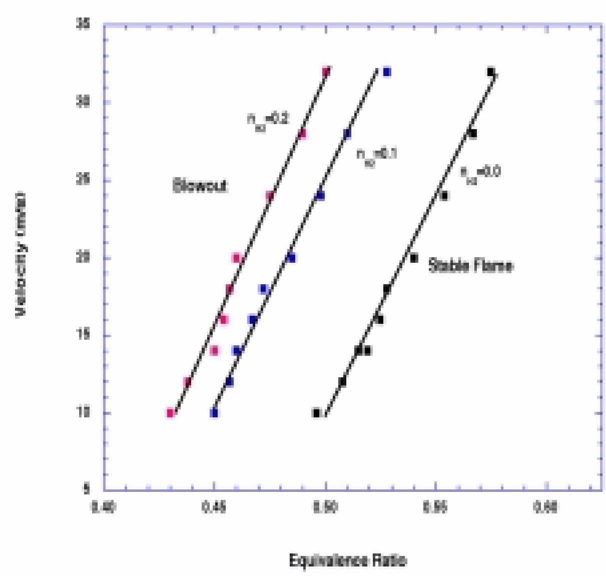

Figure 2. Effect of Hydrogen Addition on Flame Stability in Lean Swirl Burner

A previous study analyzed the potential of controlling NO_x emissions with the addition of hydrogen [1]. It was found that up to 20% hydrogen addition is a competitive alternative to traditional NO_x control technologies, providing NO_x levels of about 3 ppm. This study was extended to include the potential benefits of reduced CO_2 emissions by hydrogen addition as well as NO_x reduction. Figure 3 compares the cost of NO_x removal using H_2 addition with the costs of conventional selective catalytic reduction of NO_x ($SCONO_x$) and chemical absorption for CO_2 removal. While 60-100% hydrogen addition is not competitive with $SCONO_x$ alone, up to 75% hydrogen addition is cost competitive when the cost of CO_2 removal is included.

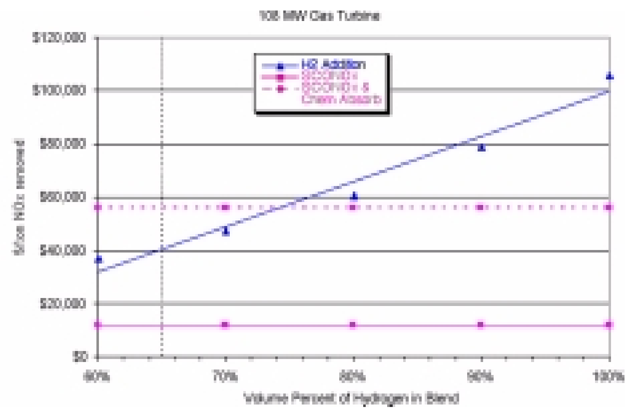

Figure 3. Cost sensitivity to percent hydrogen in natural gas. Estimated NO_x emissions are 1 ppm with high percentage CO_2 reduction.

Conclusions

- Hydrogen addition significantly improves flame stability and allows stable burner operation at the lean fuel/air ratios needed for reduced NO_x emissions.
- Up to 65% hydrogen addition for NO_x reduction to the 1 ppm level is cost competitive with current control technologies when both NO_x emissions and the cost of CO_2 removal are considered.

References

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FY 2003 Publications

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